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Predictive Modelling of ELMy H-mode JET Plasmas with 2-D Transport Code COCONUT

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1. Introduction.

It has been found in JET ELMy H-mode plasmas [1] that strong gas puffing causes an increase in ELM frequency followed by a degradation in plasma performance (see Figure 1). The level of degradation depends on the puff rate and reaches its maximum when the gas puff rate exceeds 10^{22} particles/sec and type I ELMs transform into type III ELMs. Various attempts have been made to explain such behaviour, which include role of neutrals on the Edge Transport Barrier (ETB) width [2] or the involvement of more than one instability in the ELM development [3].

To deal with these issues, the JET transport codes (1.5D core transport code JETTO and 2D SOL transport code EDGE2D/NIMBUS) have been extensively modified. In particular, better radial resolution (301 mesh points instead of 51), has been implemented, which allows us to resolve all relevant plasma parameters (pressure gradient, magnetic shear, current) to within 1 cm to ensure proper evaluation of ballooning and kink stability. It also allows us to ensure proper description of the cold neutral penetration through the SOL and the ETB

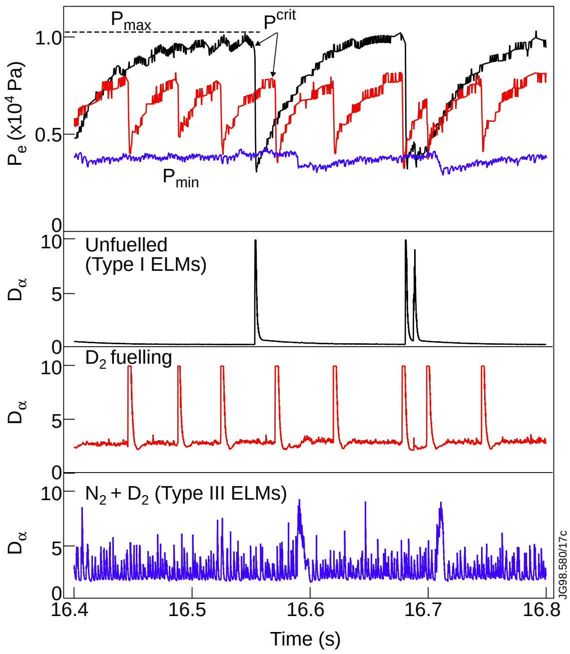

Fig.1: Pedestal pressure cycles and divertor D_α vs Time for an unfuelled discharge and identical pulses D_2 and $D_2 + N_2$ fuelling

2. Role of Fast Ions.

These improvements were used in the extensive 2D transport modelling of a series of JET ELMy H-mode plasmas, which were identical in all respect but for the rate of gas puff. The basic assumptions about the transport model, used in the modelling, have been discussed previously in [2]. It is worth mentioning here however, that the model, used in these simulations, triggers an ELM only if the ballooning stability limit has been exceeded. Each individual ELM is modelled by a short (<1msec) increase in all the transport coefficients within the edge barrier. It does not deal with either kink or the peeling mode stability. First results concluded that the variation of ELM frequency and confinement degradation can be adequately reproduced with standard JET Bohm/gyroBohm model [4] with an assumption that ETB width Δ shrinks with the gas puff. This contraction (from Δ=3 cm for discharge without gas puffing to Δ<1cm for discharge with strong puffing) is much stronger than is anticipated by the commonly used scalings:

$$\Delta\propto {}^{\mathrm{th}}_{\theta i} \text{ or } \Delta\propto \sqrt{\rho^{\mathrm{th}}_{\theta i}\cdot R}$$

Therefore we can conclude that we still do not have an adequate explanation of such fast variation of ELM frequency. The other issue to be addressed is what instability actually triggers the ELM - ballooning or kink/peeling.

Let us first discuss the issue of transport barrier width. It was proposed in [5] that collisional loss of fast ions (produced by the NBI heating) could account for a noticeable difference in ELM behaviour between NBI and ICRH heated plasmas. And, actually, experimentally observed ETB width of Δ =3 cm is in a good correspondence with the banana width of fast rather than thermal ions. On the other hand, Δ <1cm corresponds to a thermal ion banana width. Simple estimations show [5] that fast ion losses could influence the ETB width if the ratio of fast ion density over the thermal ion density exceeds certain level of the order of:

$$\frac{n_i^{fast}}{n_i^{th}} \geq \frac{\rho_{\theta i}}{R} \geq 10^{-2}$$

A possible hypothsesis is therefore that strong gas puffing might wipe out fast ions from the edge due to their charge exchange collisions with cold neutrals so that the ETB width begin to be controlled by thermal ions (like in the case of ICRH heated plasma).

Theoretical analysis shows that a neutral particle flux in excess of $\Gamma \geq 10^{22} sec^{-1}$ should be adequate to reduce significantly the population of fast ions inside separatrix in JET. Our 2-D modelling of JET plasmas including the SOL have shown (see Figure 2) that this is indeed of the order of the maximum level of neutral influx which penetrates through the SOL and reaches ETB. This allows us to propose the following explanation to the experimentally observed fast increase of ELM frequency with gas puffing. Each type I ELM expels fast particle from plasma edge so that the ETB width is controlled by the losses of thermal ions immediately after the ELM. This gives the following estimation for the transport barrier width $\Delta_{th} \approx \sqrt{\varepsilon} \cdot \rho_{\theta i}^{th}$ after an ELM. Gradually NBI builds up the population of fast particles near the separatrix.

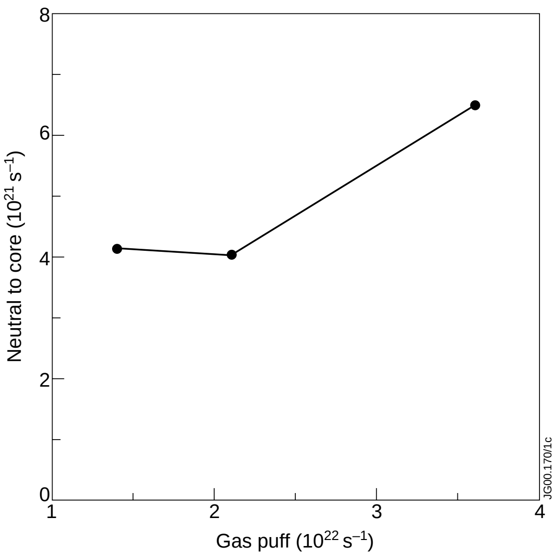

Fig.2: Calculated cold neutral influx as a function of external gas puffing rate

The characteristic time for such built up is a fast ion slowing down time $\tau_{slow\text{-}down} \propto \nu_{ii}(E_{beam}) \propto$ 100m sec. We can say that in case of adequate NBI power ETB width expands gradually from to so that: $\Delta_{th} \approx \sqrt{\varepsilon} \cdot \rho_{\theta i}^{th}$ to $\Delta_{beam} \approx \sqrt{\varepsilon} \cdot \rho_{\theta i}^{beam}$ so that:

$$\Delta \approx \Delta_{th} + (\Delta_{beam} - \Delta_{th}) \cdot \left(1 - \exp\left(- \frac{t - t_{ELM}}{\tau_{sl\text{-}down}} \right) \right) \qquad (1)$$

Charge exchange losses reduce an accumulation rate of fast ions, which in effect increases their accumulation time. An extensive modelling of JET ELMy H-mode plasmas with different level of gas puffing and with Δ_{th} = 1cm and Δ_{beam} = 3cm has been done with some results presented on Figure 3. The following conclusions could be drawn from this analysis.

The easiest way to change the ELM frequency while using model (1) is to change the slowing order of . A possible hypothesis is therefore that strong gas puffing might wipe out fast ions from the edge due to their charge exchange collisions with cold neutrals so that the ETB width begindown time. The ELM frequency rises from $f_{low} \approx$ 5Hz to $f_{high} \geq$ 20Hz while increasing the slowing down time from $\tau_{slow}^{min} \approx$ 100msec to $\tau_{slow}^{max} \approx$ 200msec. Further modest increase in ELM frequency could be achieved by reducing ion temperature on the top of the barrier, which decreases edge barrier width as $\Delta_{th} \propto \sqrt{T_i}$. One should remember, however that there is a natural limit in the defined ELM frequency, since $f_{ELM} \propto \Delta^{-1}$ in present model. This implies that in the frame of our model the transport barrier width should be reduced to an unrealistically small width of less than $\Delta \leq$ 1mm in order to explain the transition to type III ELMs with $f_{ELM} \geq$ 1kHz.

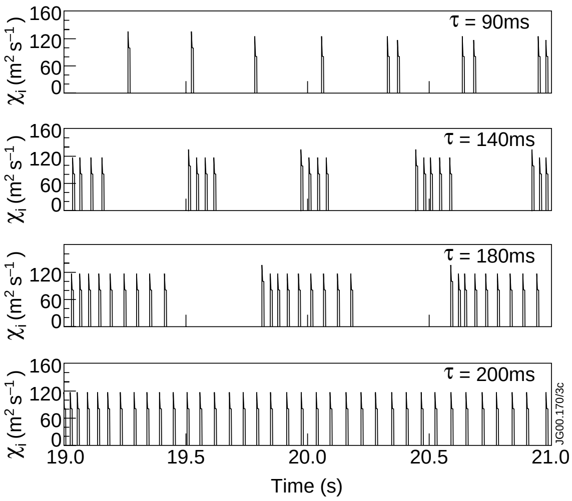

Fig.3: Simulated ELM repetition rate as a function of the beam slowing down time τ

III. The Role of Kink Instability.

Now let's discuss the possibility that kink/peeling mode plays a role as an ELM trigger [3]. Experimental observations from DIII-D and JET show that the pressure gradient inside separatrix sometimes exceeds conventional ballooning stability limit in ELMy H-mode plasma [6]. This indicates that plasma edge enters second ballooning stability region in these experiments. If so, there should be an additional instability, other than ballooning one, which triggers ELM in this situation.

We utilise a simple criterion for a kink mode destabilisation and implement it in our modelling. Namely we assume that kink mode becomes unstable if edge current density (current within ETB) exceeds certain part of an average current density: $j_z^{edge} \geq \alpha \cdot \langle j_z \rangle$, where $\alpha \approx 0.2$. Since JET transport codes are linked with the ballooning stability code IDBALL, we were able to analyse ballooning stability in a self consistent way, taking into account edge bootstrap current, which actually opens an access to a second stability region. We assume in this series of predictive modelling that there are two possible reasons for ELM emergence- ballooning and kink instabilities. We varied the ways in which these instabilities modify edge transport. In particular, we assume that ballooning instability increases equally all transport coefficients and kink instability increases electron thermal conductivity only. The result of our study allows us to draw the following conclusions.

First of all it has been found, that particular assumptions about which transport coefficients are increased during the ELM, are not very important. In this respect, ballooning and kink induced ELMs are similar- they both reduce edge current together with edge pressure. Some difference comes from the fact that the restoration of edge current usually requires more time than the restoration of edge pressure. This effectively reduces ELM frequency in case of kink instability, provided all other ingredients of ELM (like ELM amplitude) are the same.

Secondly, analysis shows that indeed edge plasma parameters in the typical JET ELMy H-mode bring the plasma edge close to an opening to a second stability regime (see Figure 4). This conclusion is very sensitive with respect to the way we calculate bootstrap current. Full inclusion of the neo-classical bootstrap current brings the system into the second stability regime.This conclusion can be easily understood by analysing the trajectory of the edge operational point in α-j co-ordinates (see Figure 4). It follows from the Figure that initial destabilisation of kink instability causes reduction in edge current together with edge pressure gradient. The former leads immediately to an increase in magnetic shear, which could make ballooning mode unstable. On the other hand, if we assume that bootstrap current is destroyed by e.g. strong collisions between ions and cold neutrals, the system looses access to a second stability.

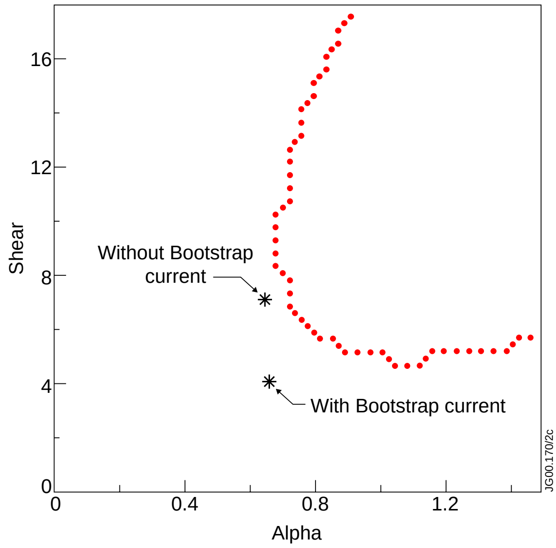

Fig.4: Ballooning stability diagram (s-α) with two operational points - with and without bootstrap

Finally, an analysis of combined kink-ballooning stability shows that ELM amplitude could be significantly increased in case when the ELM is triggered by the kink instability (see Figure 4).

4. Conclusions.

Predictive modelling has shown that accumulation of fast particles near the separatrix could increase the width of edge transport barrier and explain experimentally observed difference between type I ELMs, induced by NBI and ICRH in JET. Strong gas puffing in NBI heated plasmas could effectively reduce fast particle population near the separatrix which brings ELM frequency to that of ICRF heated plasmas. Relative role of ballooning and kink instabilities in triggering of type I ELM has been investigated.

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